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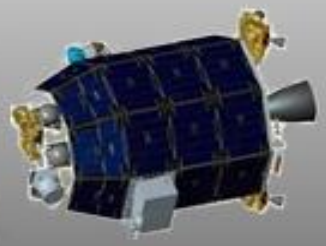

Multi-beam laser beacon propagation over lunar distance: comparison of predictions and measurements

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Outline

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- **Introduction**
- **Multi-beam beacon laser configuration**
- **Measured data**
- **Link Analysis Verification**
- **Variable Beam Divergence and Power**
- **Uplink Simulations**
- **Simulations & Measurements**
- **Conclusions**

Introduction

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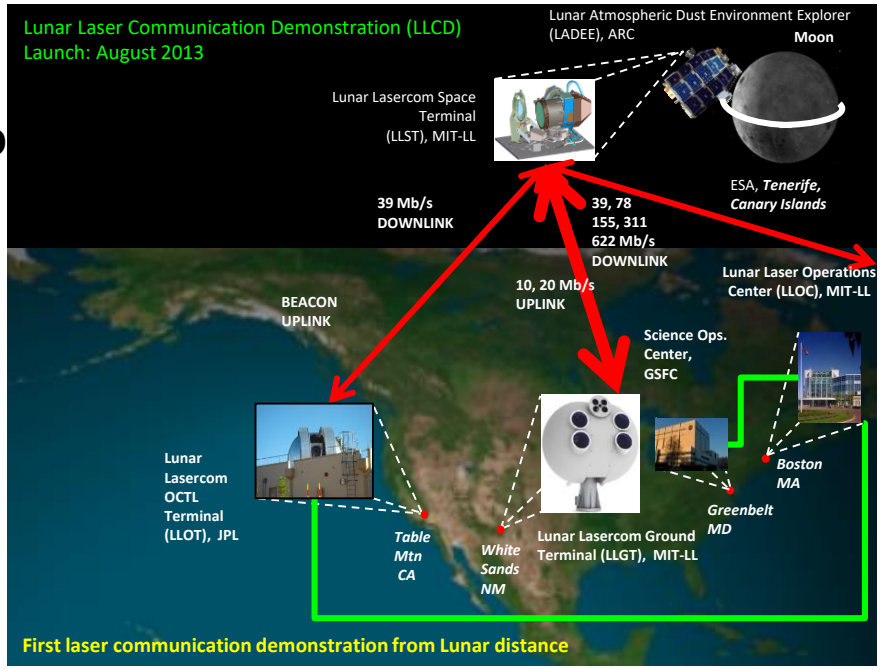
- **NASA's Lunar Laser Communication Demonstration LLCD occurred in 2013**
- **The OCTL telescope at Table Mountain, CA served as an alternative ground station**
- **Multi-beam (6×) laser beacon at 1568 nm was transmitted**
- **The Lunar Lasercom Space Terminal (LLST) received the beacon signal on a quadrant PIN diode**
  - 1 kHz modulated beacon
  - Processed on-board to compute incident power
  - 5 kHz sampled time series telemetered down over downlink
- **Post processed codewords downlinked to OCTL at Lincoln Laboratory, MIT**
- **Analyzed uplink data in order to :**
  - **Verify Uplink budget (< 1 dB)**
  - **Confirm variable beam divergence using zoom**
  - **Compare measured scintillation index with wave propagation model derived for Table Mt., CA**



Multi-beam beacon laser configuration

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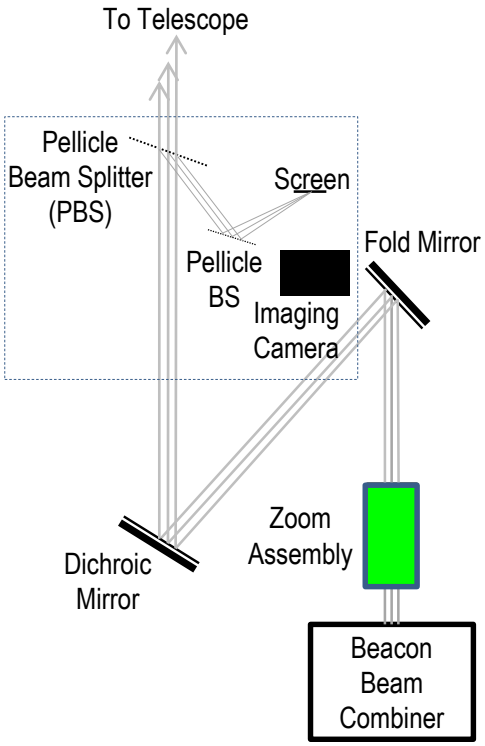
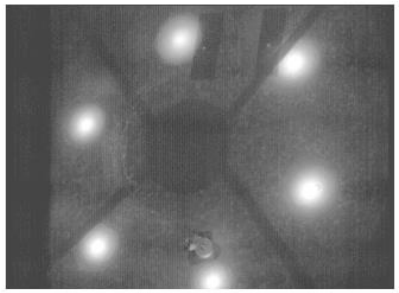
- **Optical train coupling multi-beam to 1 m telescope had a built in**
  - Zoom Assembly (*green box*)
  - Beacon Monitoring Assembly (*dashed line box*)

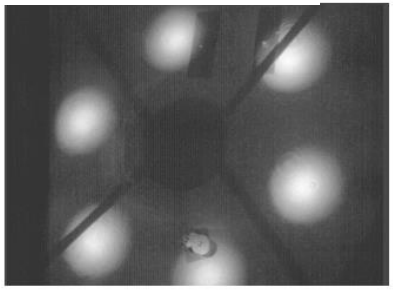
- **Exercised both during LLCD operations**

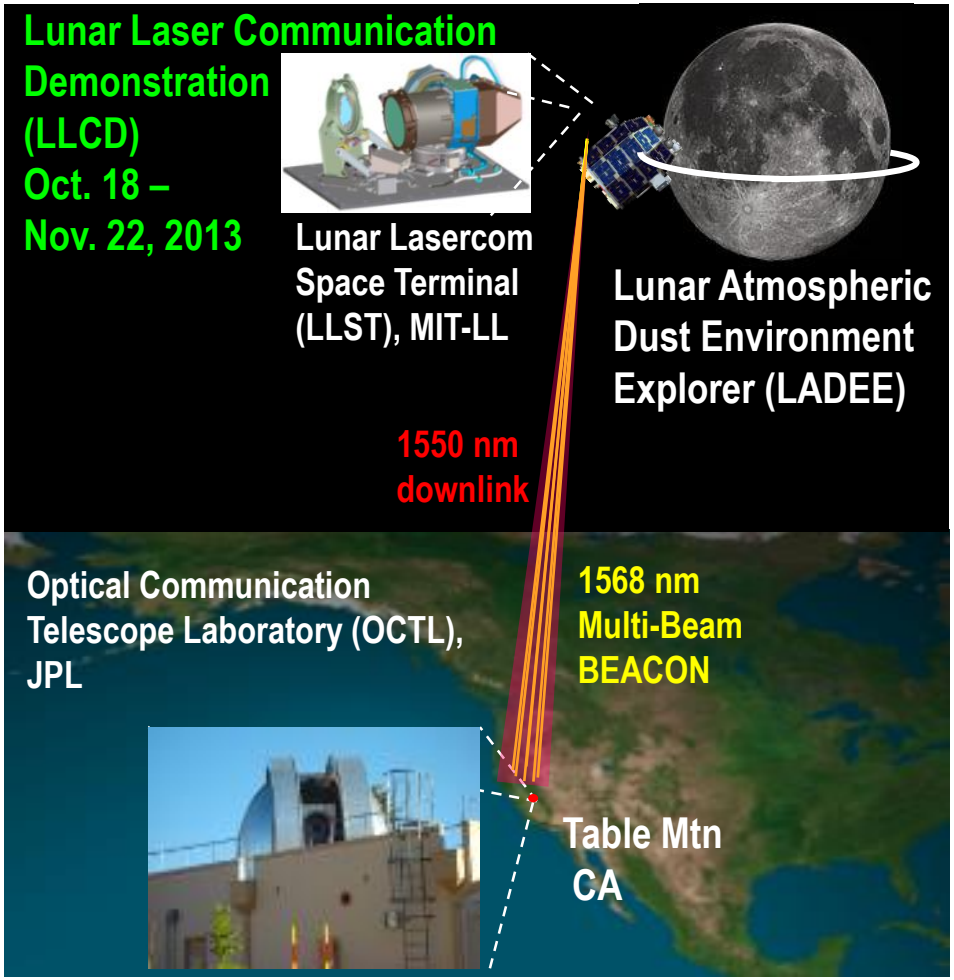


Zoom extremity 1 (110 μrad)



Zoom extremity 2 (40 μrad)





Example data series

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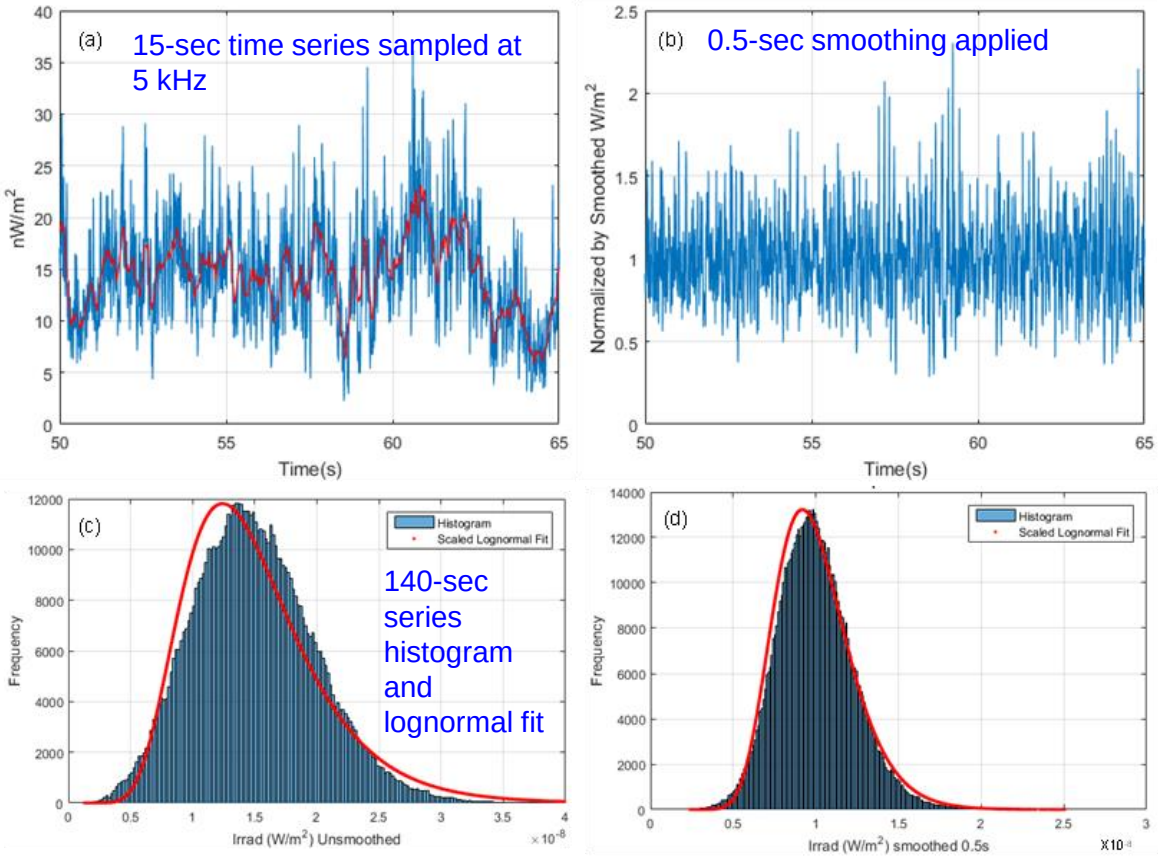
- **Converted typical power time series (shown below) to irradiance**
- **Time series displayed fluctuations at two time scales**
- **0.5 second smoothed series taken to represent atmospheric turbulence induced scintillation**
  - Fit to lognormal distribution supports this
  - Slower time series needs further study
- **Used time series to obtain:**
  - Compute **mean irradiance**
  - Normalized variance or **scintillation index** ion smoothed data
  - **Coherence time** using autocorrelation function



Link Analysis Verification

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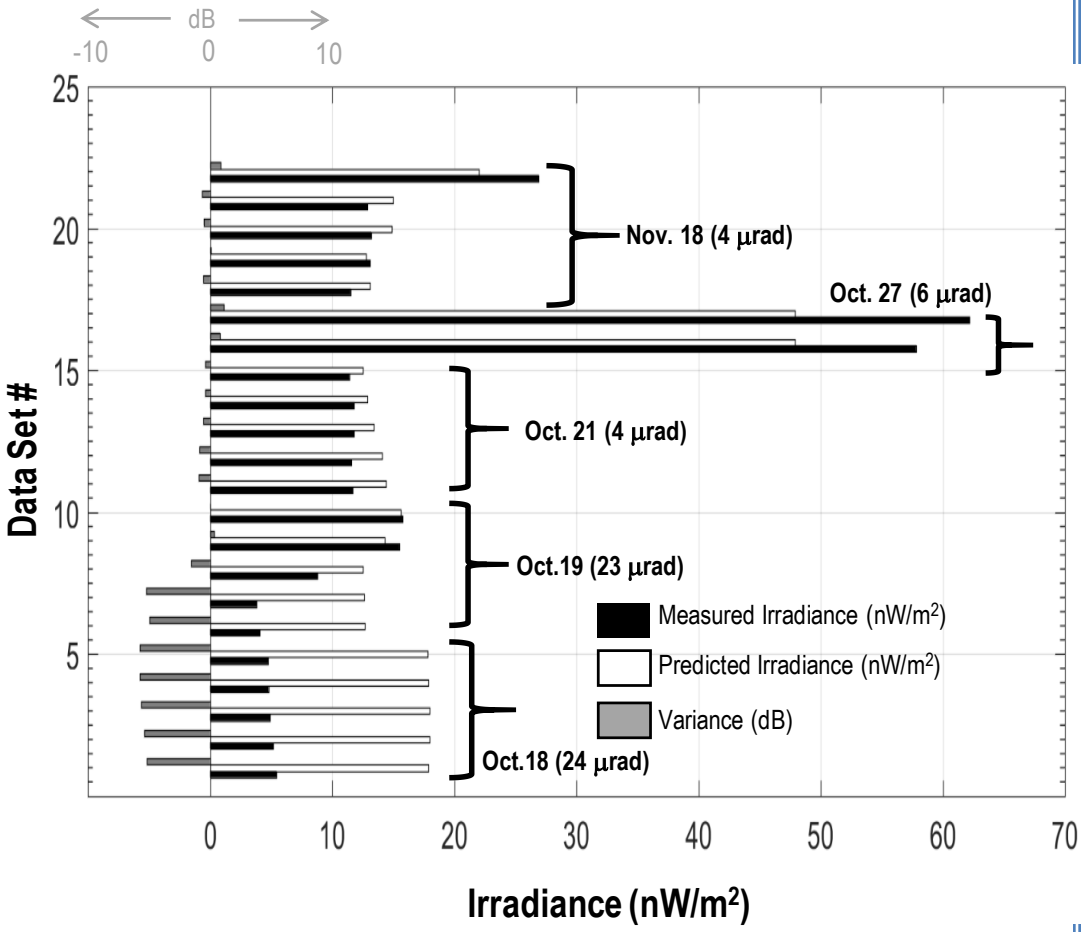
- **Analyzed link budget for a few passes (Oct.18 - Nov.18, 2013)**
  - Used ground stored telemetry – elevation angle, laser power, beam divergence, pointing offset
  - Fixed atmospheric attenuation was used for all the computations

- **Obtained good agreement**
  - With pointing offset was small (< 5 μrad) deviations of **< 1 dB**
  - When pointing offset was large 23 μrad the deviations in 7 out of 9 data-sets was **~ 5 dB**
  - Conjecture that pointing offset may have been worse than what monitoring assembly was inferring
  - Lesson learned
    - Beam divergence and pointing offset monitoring is very useful for post analysis
    - Mechanical drift of commercial mounts needs re-alignment prior to pass
    - Automated systems recommended for future operational systems



Variable Beam Divergence and Power

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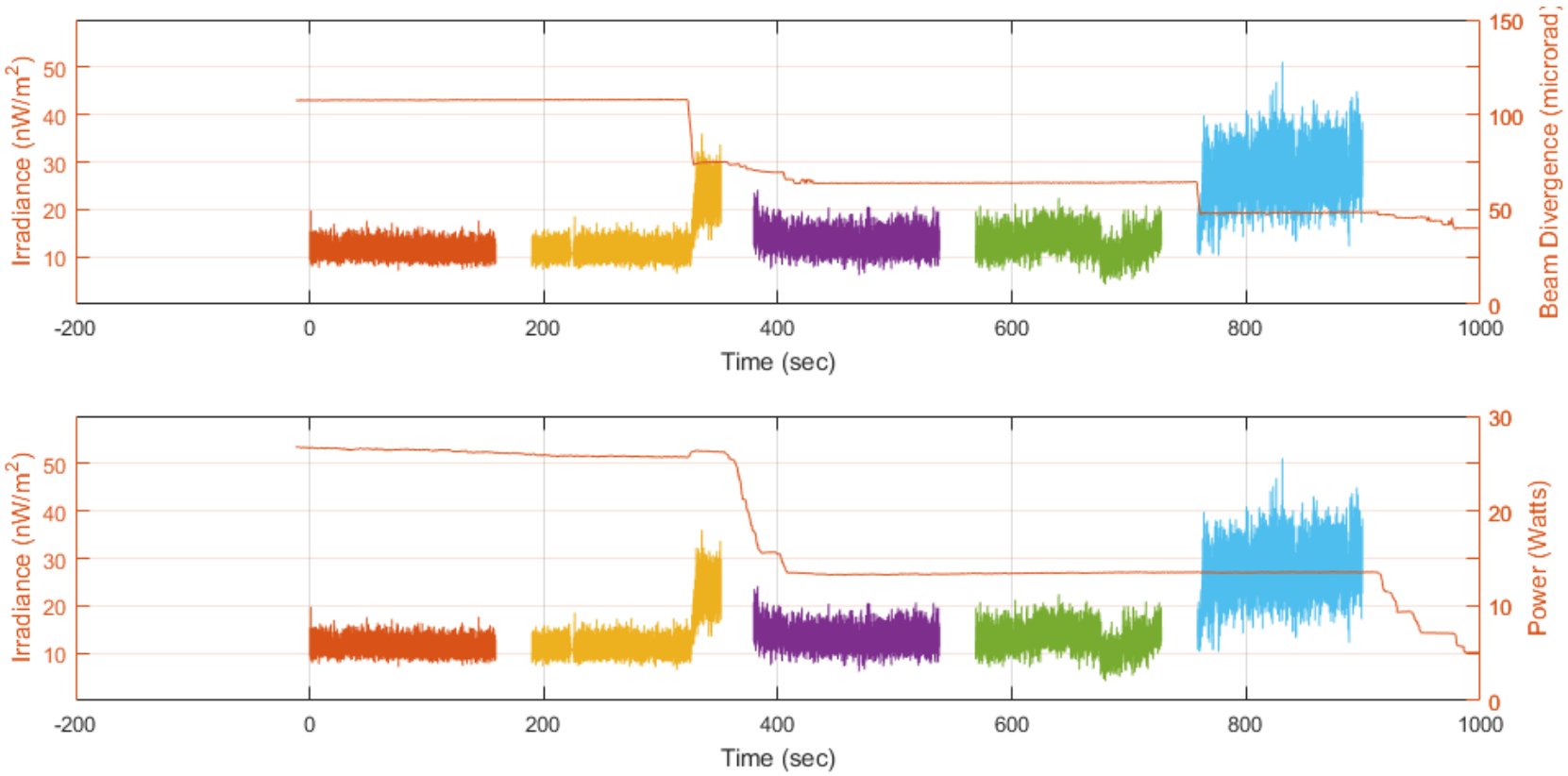
- **During a few links transmitted beam divergence was varied using zoom assembly and power was decreased**
  - Irradiance on target responded as expected when using the zoom to change divergence
  - Results verify both the zoom assembly and monitoring assembly



Uplink Simulations

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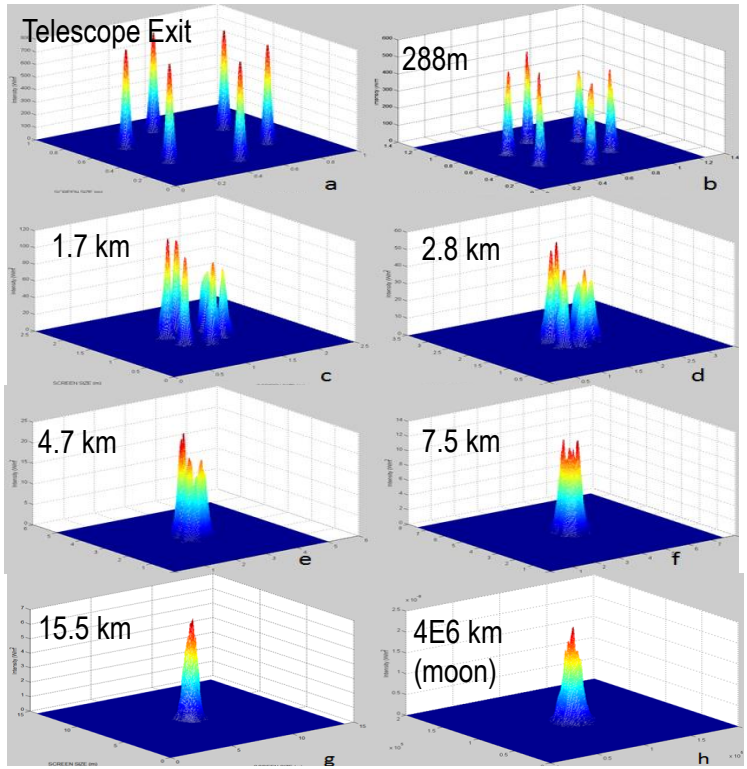
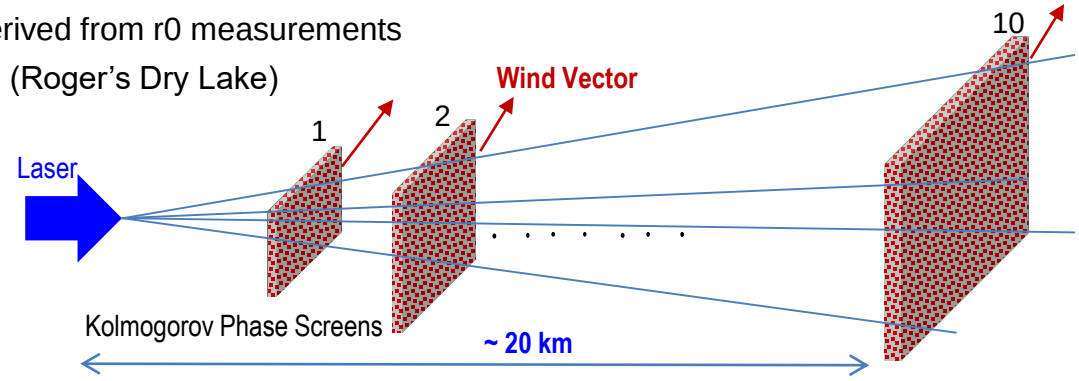
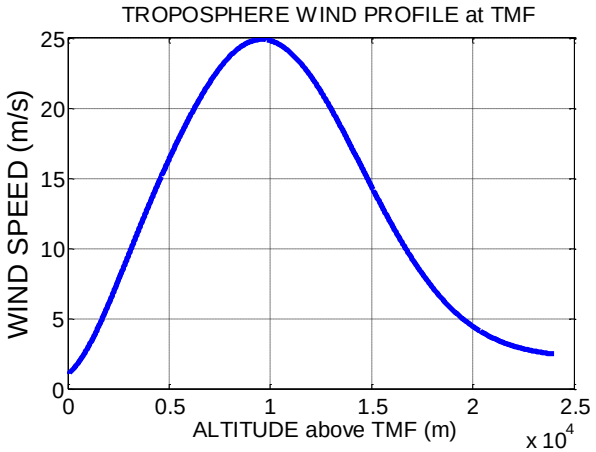
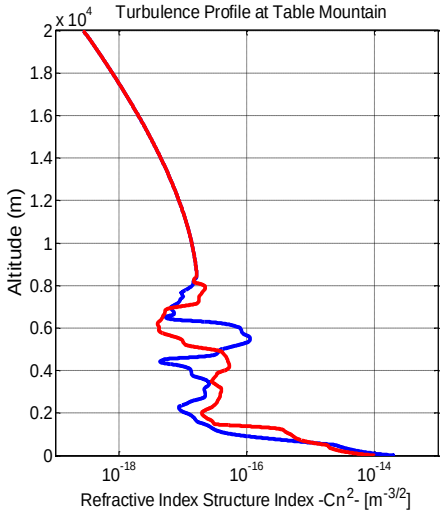
- **Simulated uplink laser propagation with 10 Kolmogorov phase screens**
  - Each phase screen represents an atmospheric layer
  - 2-D fast Fourier transform (FFT) used to propagate of the electromagnetic wave
  - Obtained time series with a **1 ms** update rate
  - Input parameters matched to channel conditions at time of LLLCD uplink, as closely as possible
    - Derived a wind profile combining ground wind speed/direction with published high altitude seasonal profiles for SW US
    - Atmosphere structure function coefficient wa derived from r0 measurements
      - Measurements from nearby SW US location (Roger's Dry Lake)









Simulations & Measurements

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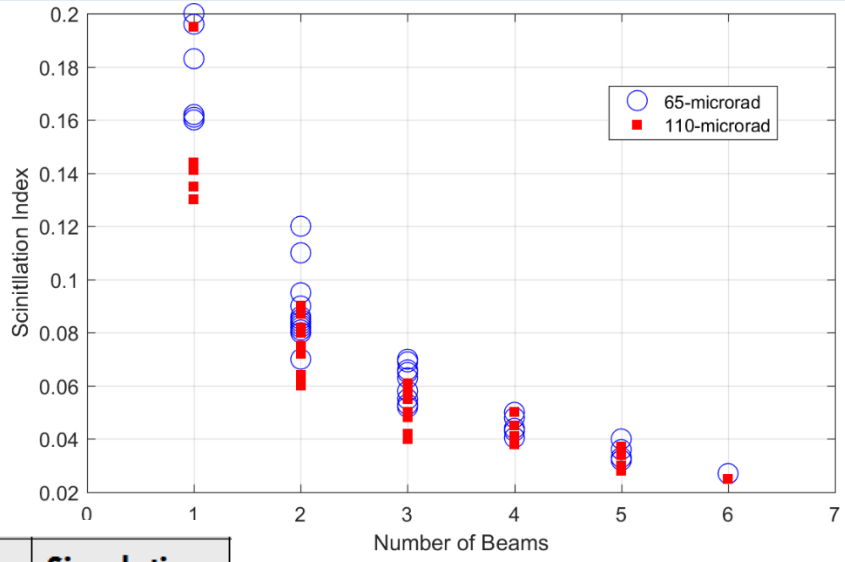
- **Simulated scintillation index fro multi-beam uplink beacon**
  - Chose pass performed on November 18, 2013 pass 12:03 12:22 UTC
  - Tranverse wind speed 0.8 m/s (100-130° azimuth)
  - r0 = 6 cm at zenith at 500 nm
  - Two 3-second duration time series generated by the simulation
  - Beam divergence was 65 and 110 μrad
- **Compared simulation to measurements**



Link	Measured Scintillation Index	Simulation Scintillation Index	Measured Coherence Time (ms)	Simulation Coherence Time (ms)
Pass 20 at 65μrad Divergence	0.018	0.027	22.4	15.9
Pass 20 at 100μrad Divergence	0.011	0.025	9.8	5.0

- Simulation results are consistent with measurement - somewhat higher
- Assumptions made in deriving simulation wind and Cn2 profile caste some uncertainty
- Measured and simulated coherence times are consistent with scintillation index results

- Validates use of simulations as a design aid for predicting multi-beam uplink beacons

Conclusions with closing thoughts

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- **Uplink beacon power time series measured during LLCD was analyzed**
- **Link budgets predicting mean irradiance were verified to < 1 dB**
- **The use of a zoom assembly to vary beam divergence was verified**
- **Approach used for real-time monitoring of beacon divergence was verified**
- **Wave propagation simulations compared favorably with measurements**
  - **The variance needs further investigation**
- **Longer term fluctuations observed in uplink power need further study**

The help provided by Dr. Bryan Robinson of LL-MIT in supporting the post processing of LLCD downlink received at OCTL is gratefully acknowledged

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